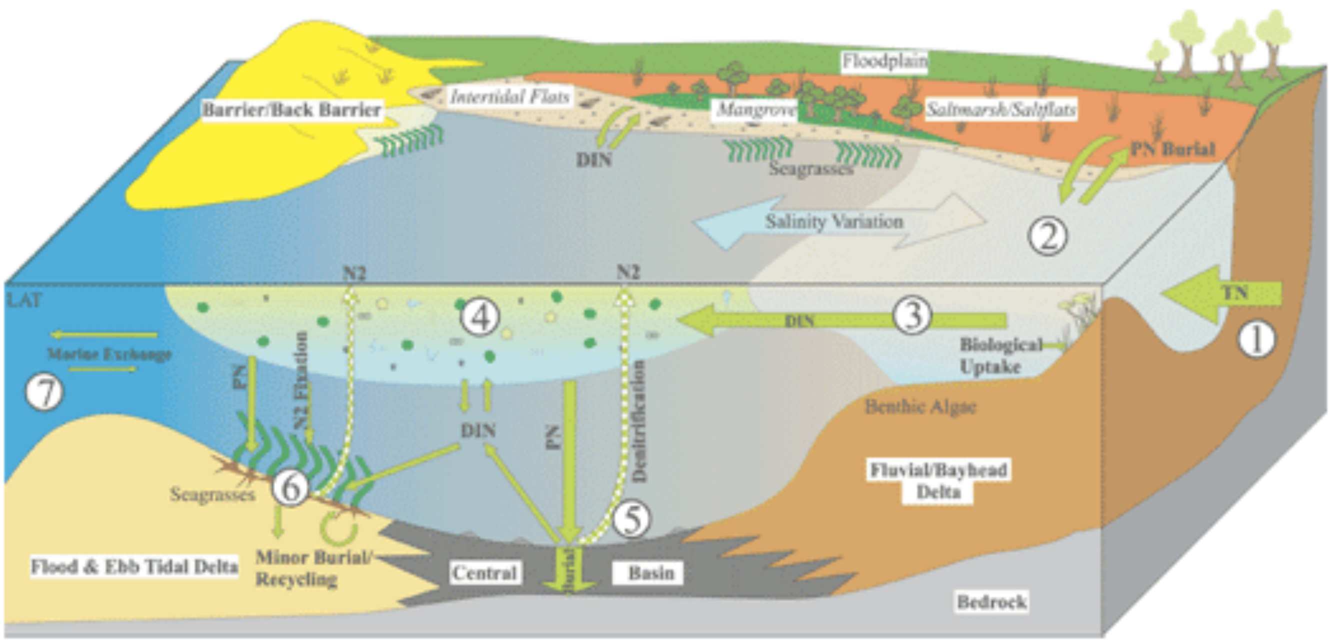
ESTUARINE CIRCULATION:
WHY SHOULD YOU CARE?

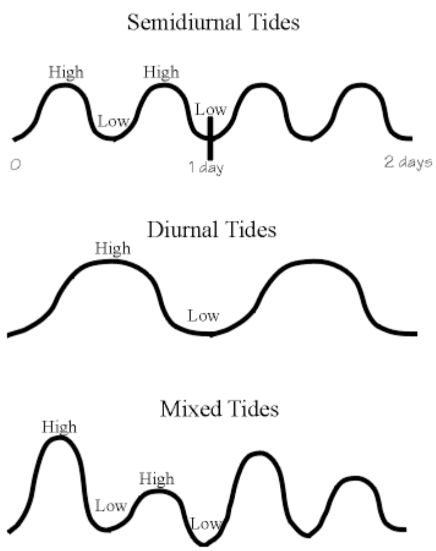


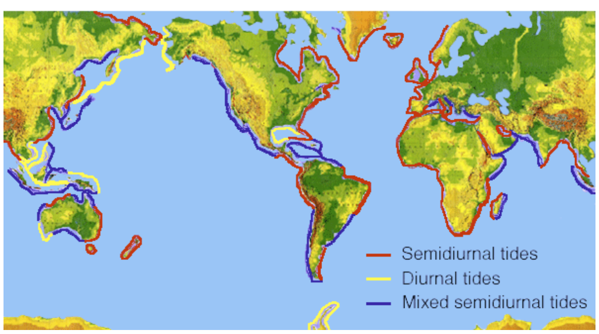
It's all a moving target

Water Inputs

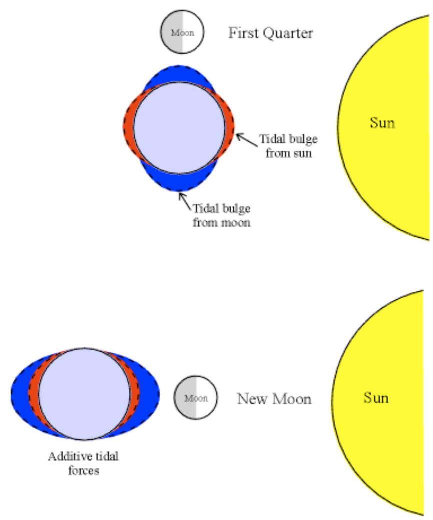
aestus = Latin for tide

Hour time scale





Week time scale



Travelling upstream, tides are delayed and deformed f(shape, depth, tidal range:depth)

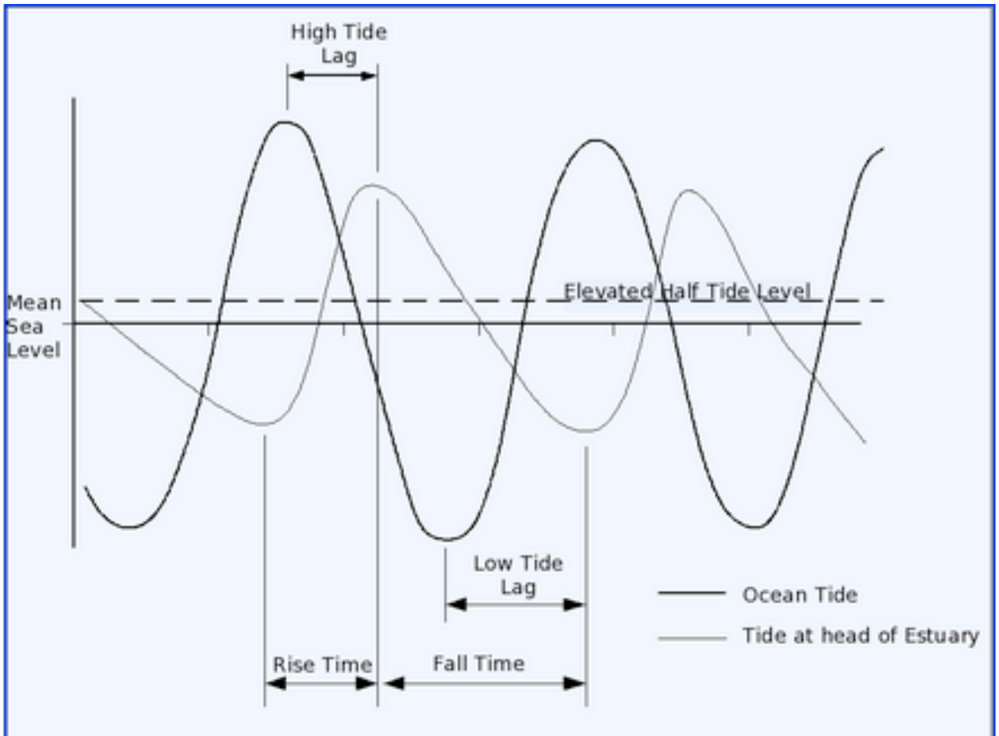
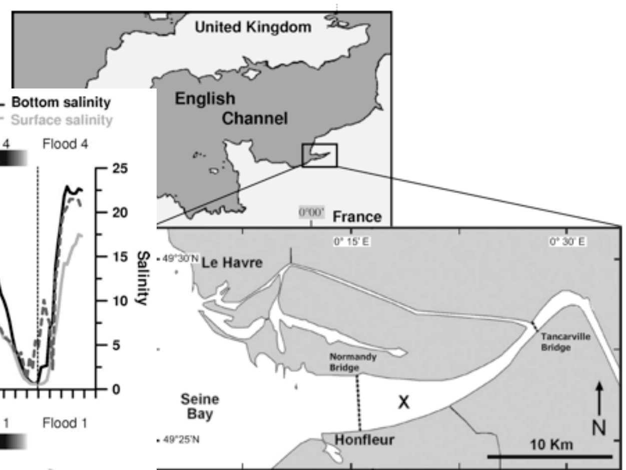
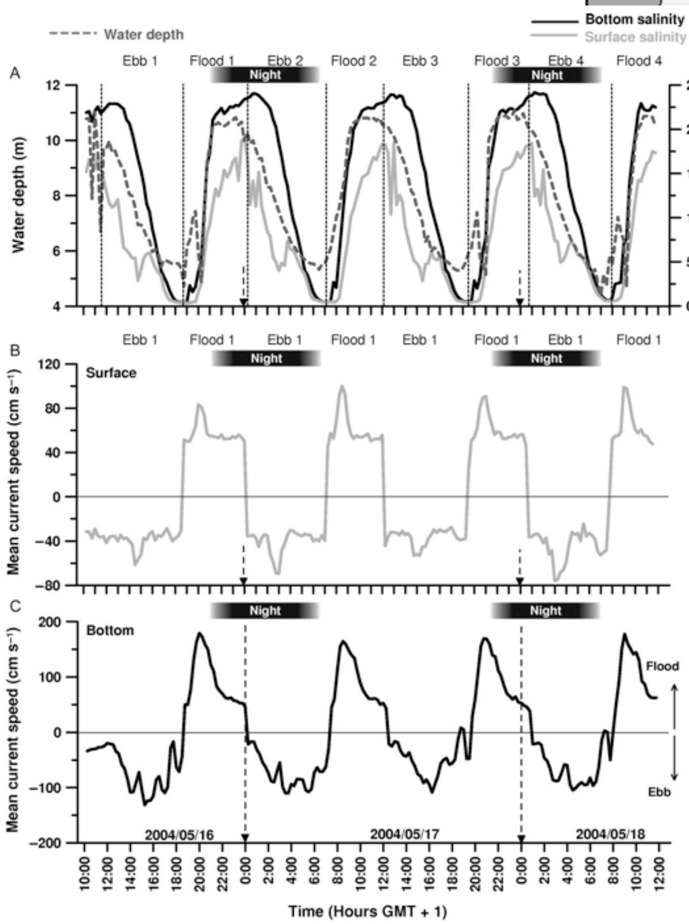


Figure 15 Tidal Characteristics at the Entrance and Head of a Tidal River

http://www.dnr.nsw.gov.au/estuaries/factsheets/physical/tidal-behaviour.shtml





And complicated

J. Plankton Res. (2008) 30 (12): 1329-1342.

Tidal filling of estuaries, and even higher

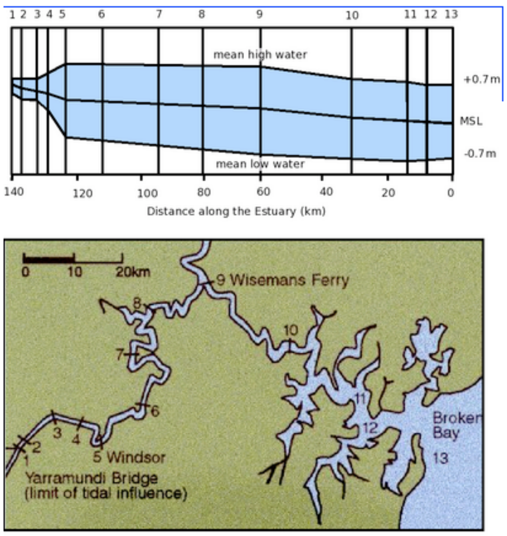


Figure 18 Tidal Characteristics of a Drowned River Valley Estuary - Hawkesbury River

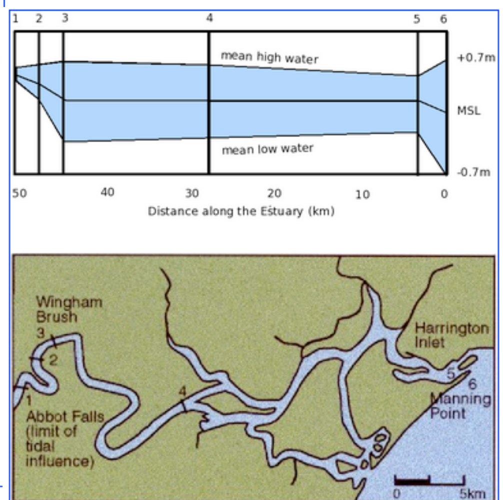


Figure 17 Tidal Characteristics of a Tidal River Manning River

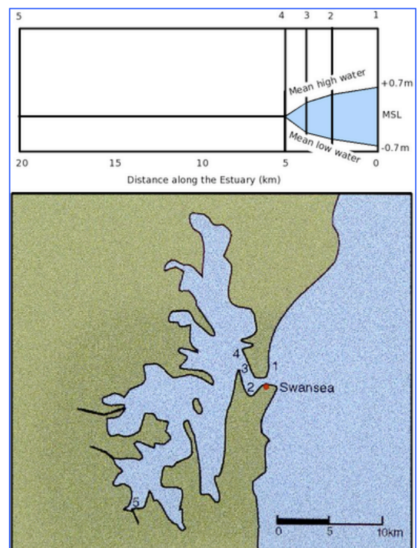


Figure 19 Tidal Characteristics of a Tidal Lake Lake Macquarie

Tidal Prism =

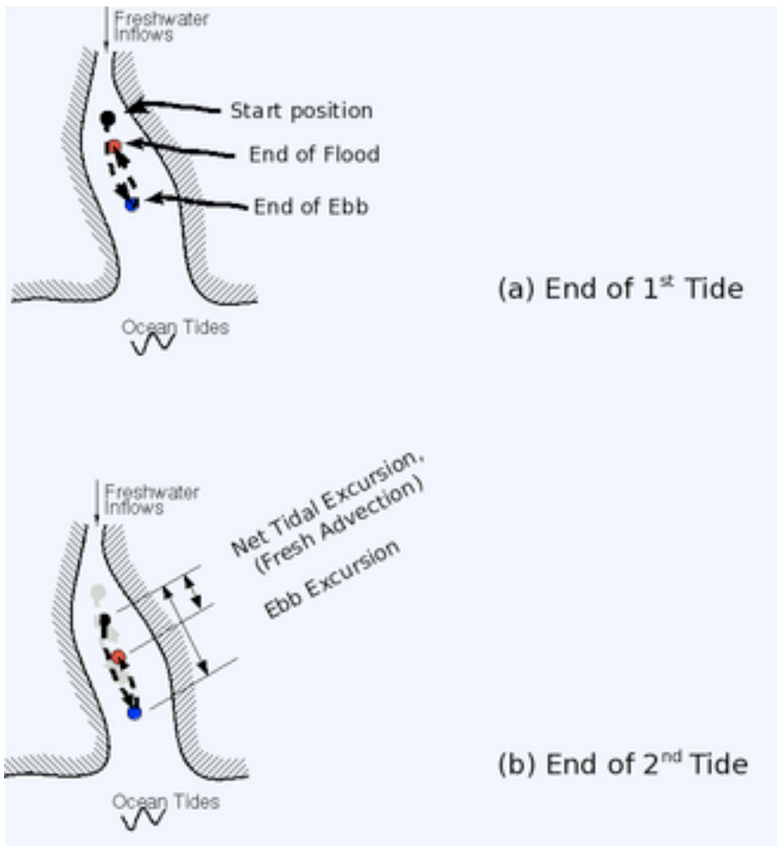
http://www.dnr.nsw.gov.au/estuaries/factsheets/physical/tidal-behaviour-nsw.shtml

--> another way to classify estuaries

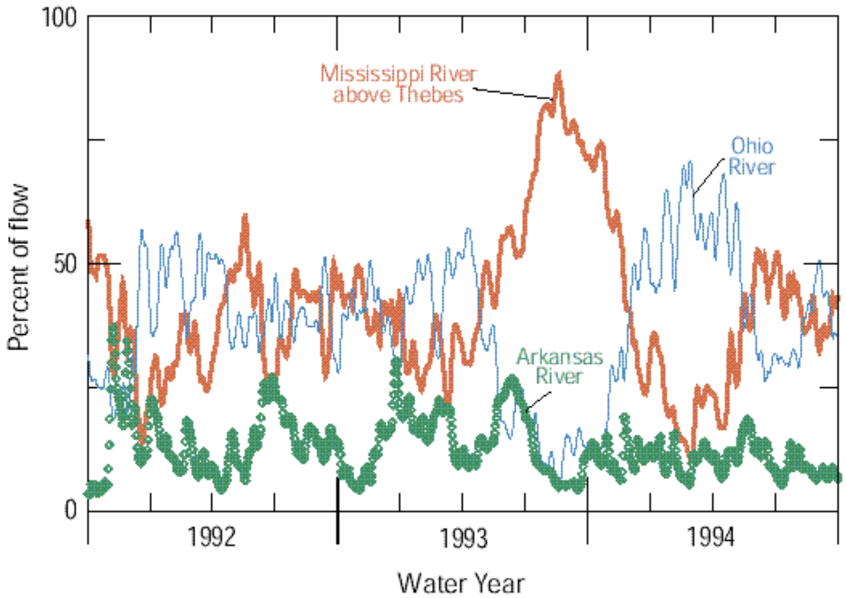
Classification by Tides Davies (1964)

Microtidal	<2m
Mesotidal	<4m, >2m
Macrotidal	<6m, >4m
Hypertidal	> 6m

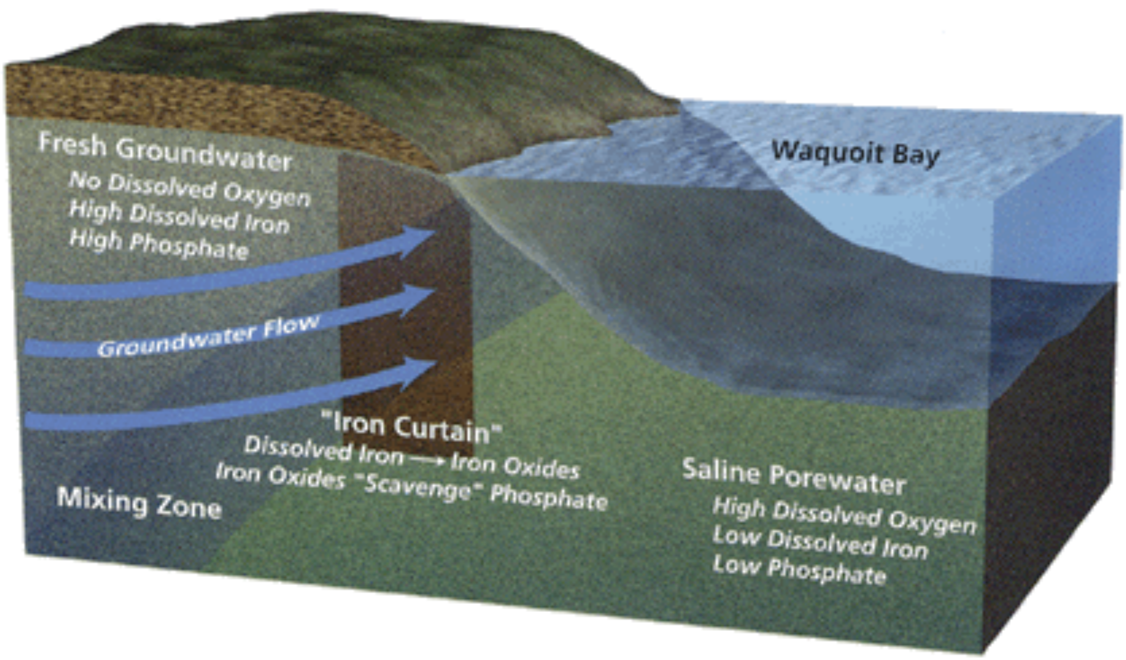
Tidal excursion



River input varies on different time scales



Groundwater inputs - the subterranean estuary



http://www.whoi.edu/oceanus/viewImage.do?id=15285&aid=7700

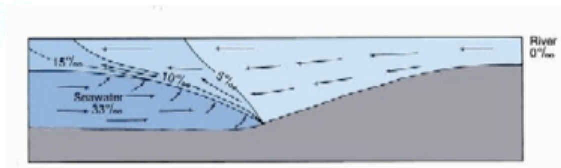
Mixing river and ocean: The Basics

A circulation-based classification scheme

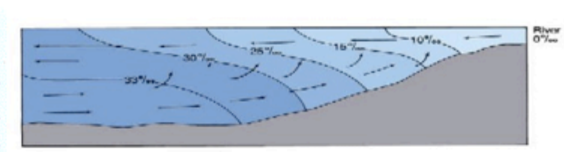
What's wrong with these pix?
Statics vs dynamics

mixing chambers

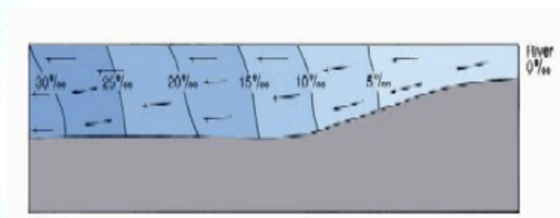
- Salt wedge estuary: controlled by rate of river discharge in a thin layer above a salt wedge



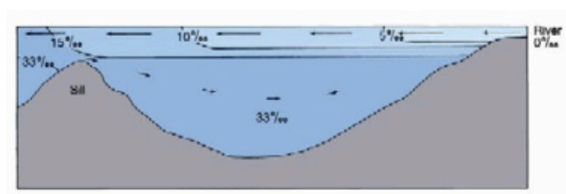
- Partially mixed estuary: strong surface river flow and strong inflow of seawater at the bottom



- Well mixed estuary: strong tidal mixing and low river flow



- Fjord-type estuary: least mixed, weak tidal flows, stratification; fresh water at the surface, seawater enters slowly at depth. The bottom water in fjords may become stagnant and anoxic due to slow rate of replacement.



What properties or processes would affect vertical mixing?

Delta-density (i.e. stratification) vs stirring

some considerations:

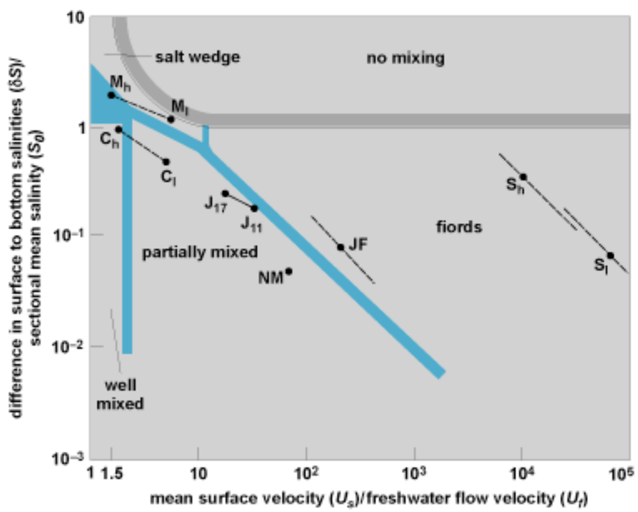
1. Morphological (shape, roughness)
2. River flow
3. Tide (magnitude, direction)
4. Wind
5. Water temperatures
6. Water compositions
7. Rainfall, evaporation
8. Time

combinations thereof...

http://www.easycalculation.com/physics/classical-physics/water-density.php
or
http://www.earthwardconsulting.com/density_calculator.htm

Classifications based on effect of river flow on stratification

Fig 3.



(Hansen-Rattray diagram)

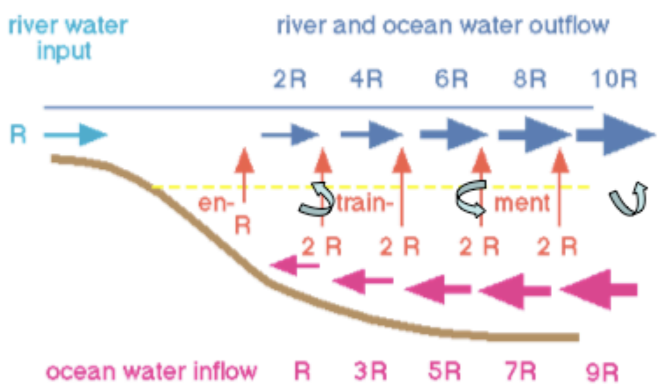
why? not always true

Fig. 3 Classification diagram for estuaries. An estuary appears as a line on the diagram; the upper reaches are less well mixed than the lower sections. Subscript letters refer to high (h) and low (l) river discharge; subscript numbers are distances from the mouth. J = James River; M = Mississippi; C = Columbia River; NM = Narrows of the Mersey; S = Silver Bay; JF = Strait of Juan de Fuca. (*After D. V. Hansen and M. Rattray, Jr., New dimensions in estuary classification, Limnol. Oceanogr., 11:319–326, 1966*)

Bowden (1980) scheme	$V_{FW}:V_{total}$
Salt-wedge	1
Partially mixed	0.1
Well-mixed	0.01

EFFECT OF VERTICAL MIXING ON FLOW ALONG ESTUARY

Mass transport in a highly stratified estuary



River volume flow is R.

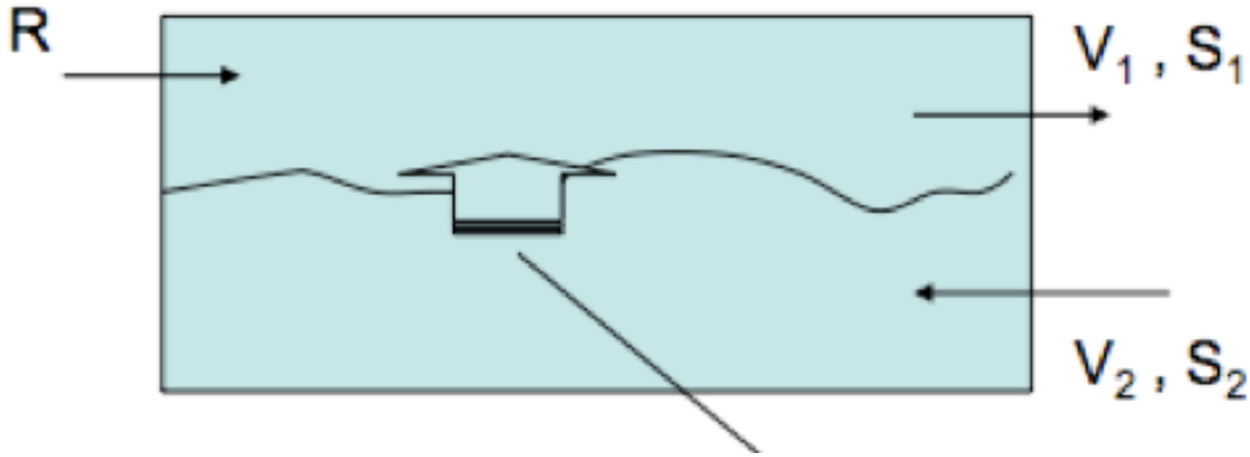
Outflow from the estuary in the upper layer is 10R.

This is balanced by oceanic inflow of 9R.

The net outflow at the ocean end is, of course, still only 1R.

http://webcache.googleusercontent.com/search?q=cache:1WEj_7OwGPsJ:marine.rutgers.edu/dmcs/ms320/2008-11-19-Estuarine-Circulation-web.ppt+coriolis+estuary&cd=1&hl=en&ct=clnk&gl=us&source=www.google.com

We can get V_1 from salt balance



V_2?

ESTIMATING SEAWARD SURFACE FLOW FROM SALINITIES (BOX MODELS)

Salt balance:

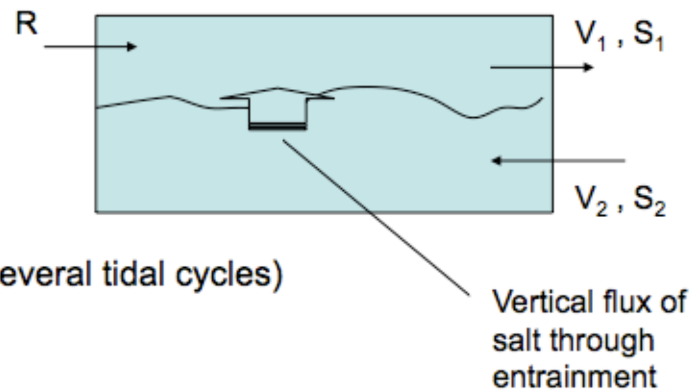
Salt in = $V_1S_1 + RS_o$

Salt out = V_2S_2

$V_1S_1 = V_2S_2$

(averaged over several tidal cycles)

$V_1 = V_2\, S_2/S_1$



Volume balance:

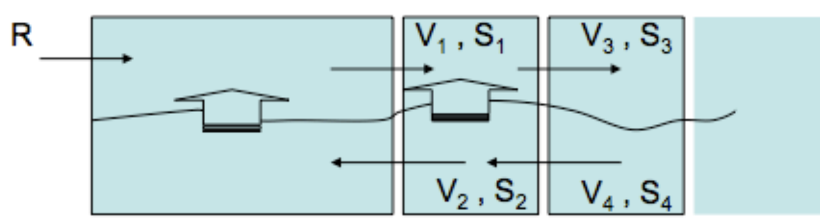
$R + V_1 = V_2$

$R = V_2 – V_1$

$= V_2 – V_2(S_2/S_1)$

$= V_2(1-S_2/S_1)$

$V_2 = R / (1 – S_2/S_1)$



Difference between upper and lower transport is always R

Neap - Spring

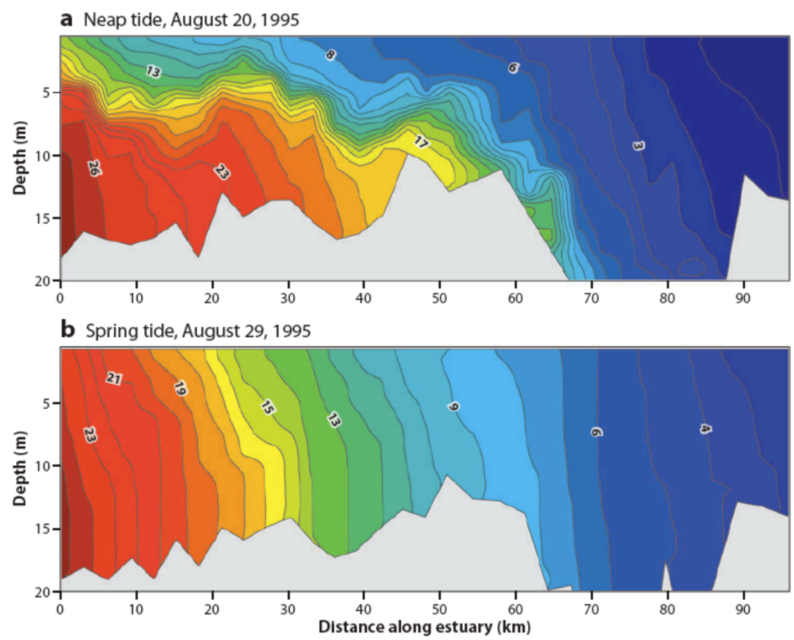
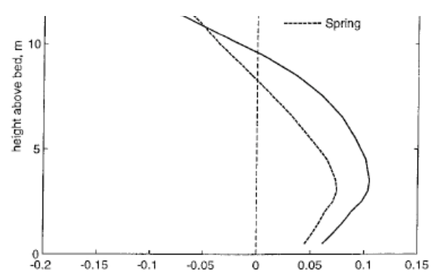


Figure 10

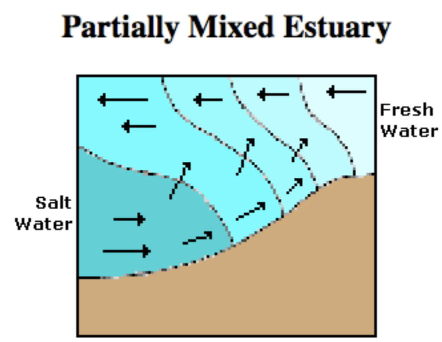
Along-estuary salinity contours in the Hudson River estuary during neap and spring tides, showing the strong spring-neap variation in stratification. The vertically averaged along-estuary salinity distribution changes only slightly, whereas the strength of the stratification changes by an order of magnitude.

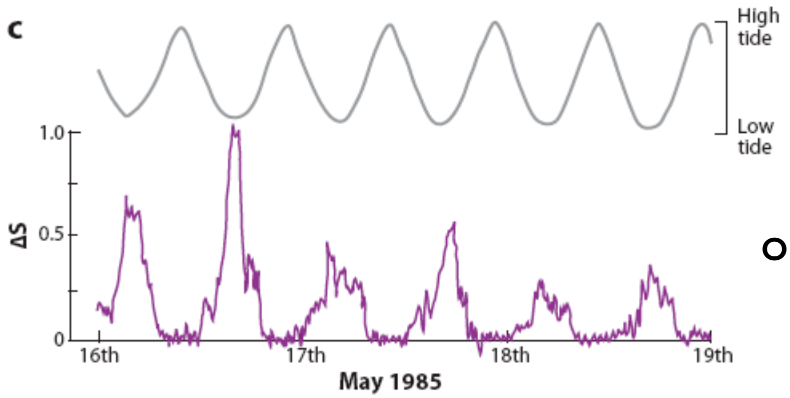
52 *MacCready • Geyer*



Geyer et al., 2000, JPO 30:2038

Stratification can change between flood and ebb because of friction with bottom (tidal straining)





one spot measurement?

Figure 7

Schematic of the tidal-straining mechanism (*upper panels*) and evidence from Liverpool Bay of the associated tidal periodicity of stratification (*lower panel*) (based on Simpson et al. 1990, reprinted with permission). The ~~top panel illustrates well-mixed conditions at the end of the flooding tide and the vertical profile of ebbing velocity. The solid lines in the second panel show the distortion of the salinity contours by the ebb, and the dashed lines indicate the influence of mixing~~. The time series in the bottom panel indicates alternation between well-mixed and stratified conditions, with maxima at the end of ebb (low tide).

Lateral effects from friction

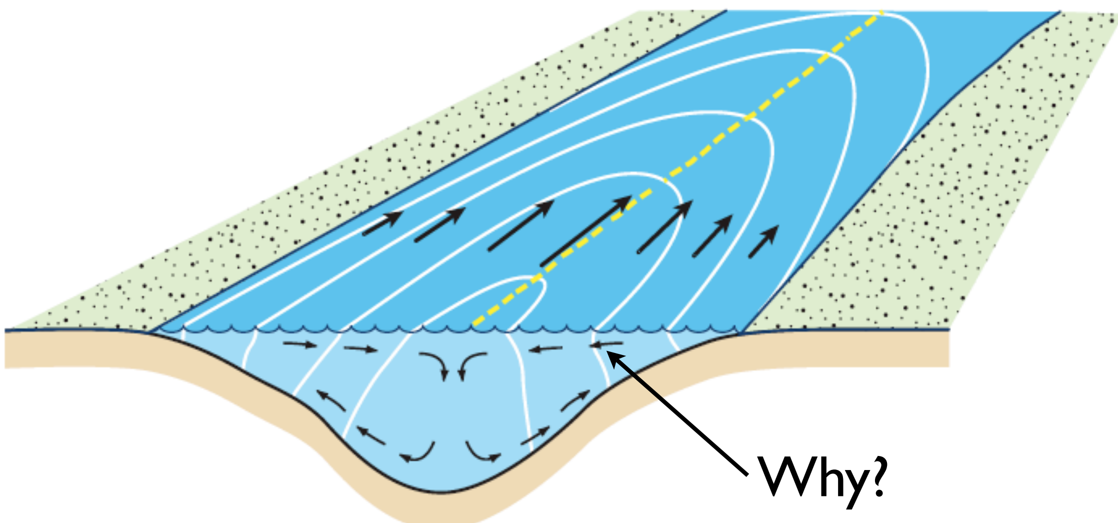


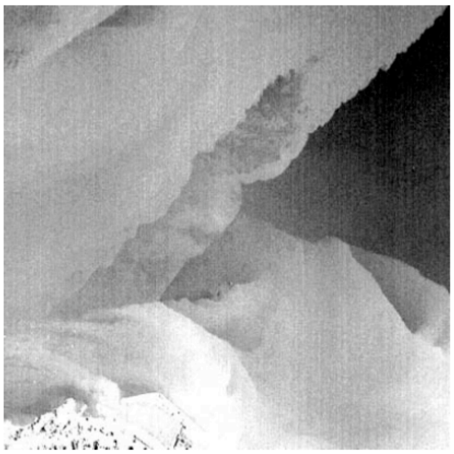
Figure 6

Schematic demonstrating differential advection during flooding tide and its influence on the lateral circulation. Along-estuary velocities (*black arrows*) are stronger in the deep part of the estuary, resulting in greater advection of higher-salinity water (*white contours*) there than on the flanks. The induced lateral density gradient drives a lateral baroclinic circulation with counter-rotating circulation cells. Surface convergence at the center results in the axial convergence front (*yellow dashed line*), as described by Nunes & Simpson (1985).

See animation at

http://getm.eu/index.php?option=com_content&task=view&id=111&Itemid=42

< Land



Ocean >

Figure 2. Thermal image of Tayport section of outer Tay Estuary acquired 45 min BHW (brighter pixels indicate higher temperature).

Tough to see with conventional hydrography

International Journal of Remote Sensing
Vol. 26, No. 20, 20 October 2005, 4399–4404

Taylor & Francis
Taylor & Francis Group

COVER

Observing estuarine currents and fronts in the Tay Estuary, Scotland, using an airborne SAR with along-track interferometry (ATI)

G. FERRIER*†, J. T. MACKLIN‡, S. P. NEILL§, A. M. FOLKARD¶, G. J. M. COPELAND** and J. M. ANDERSON***

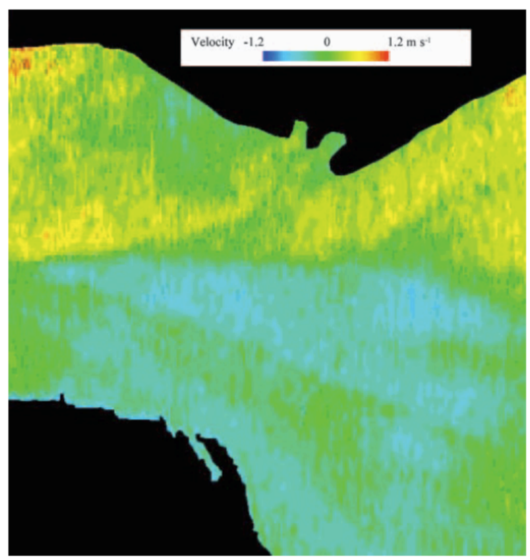
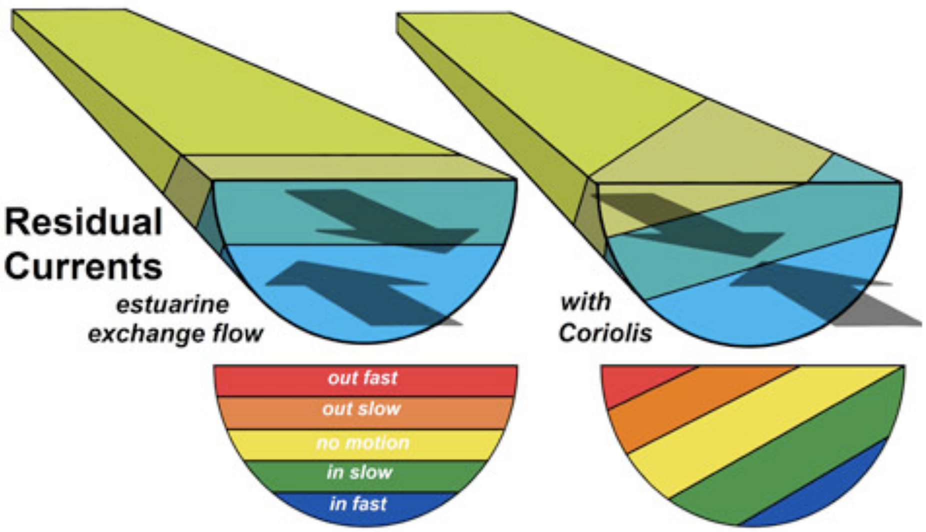


Figure 4. Range component of surface velocity inferred from InSAR phase (in $m\,s^{-1}$).

CORIOLIS EFFECTS



http://www.po.gso.uri.edu/~codiga/foster/estuarine.htm

James River estuary, note salinity differences in horizontal > those in vertical

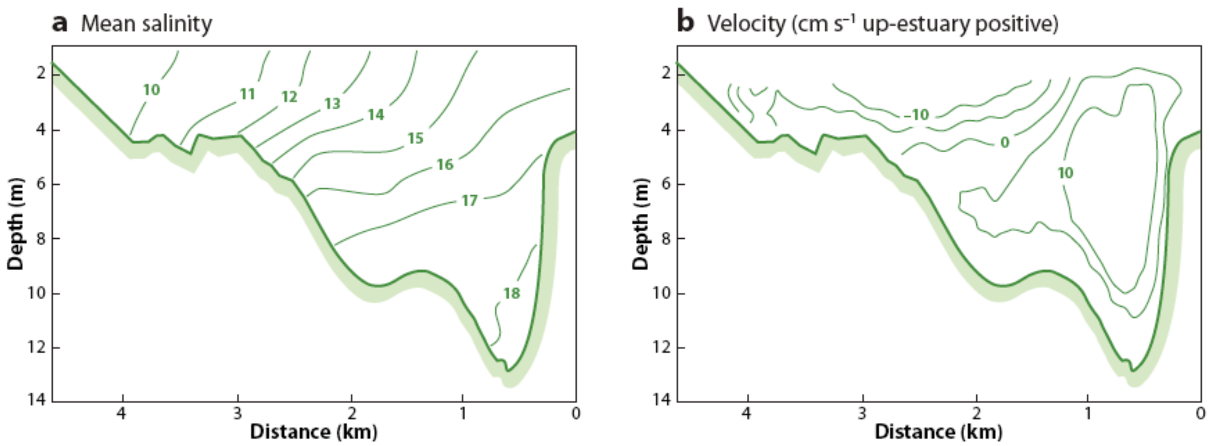
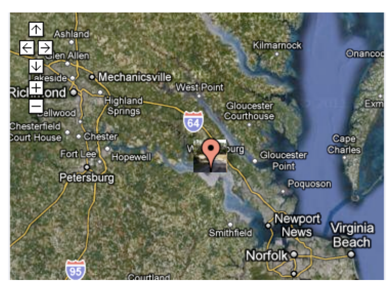
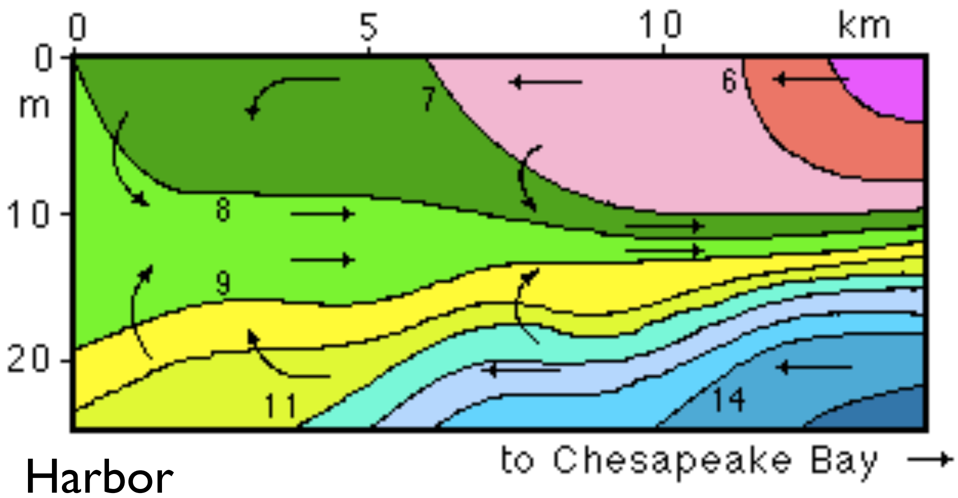


Figure 5

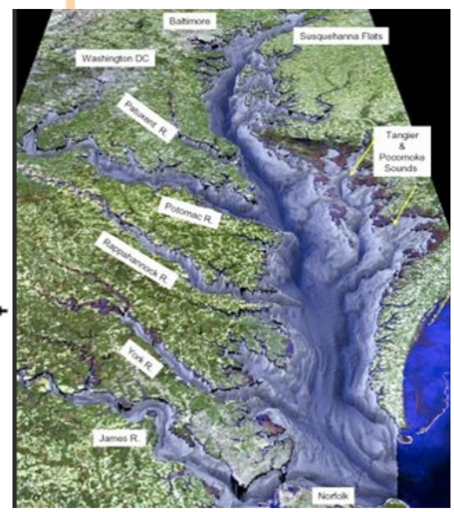
Cross-sections of tidally averaged salinity (*a*) and velocity (*b*) in the James River estuary (looking into the estuary), based on Valle-Levinson et al. (2000). The lateral variations in salinity and velocity are comparable or larger than the vertical variations, so the laterally varying residual circulation is a major contributor to the total salt flux (consistent with the findings of Fischer 1972).



Salt-plug circulation in estuarine side arms



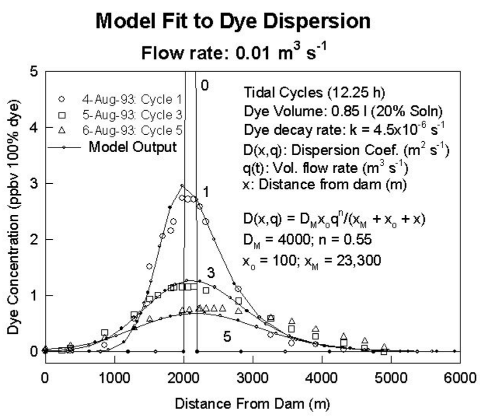
A salinity section along the axis of Baltimore Harbour, a sub-estuary of Chesapeake Bay



reinsert dam, mix one side, and pull the dam

http://www.es.flinders.edu.au/~mattom/ShelfCoast/chapter13.html

Mixing leads to Dispersion



LONGITUDINAL

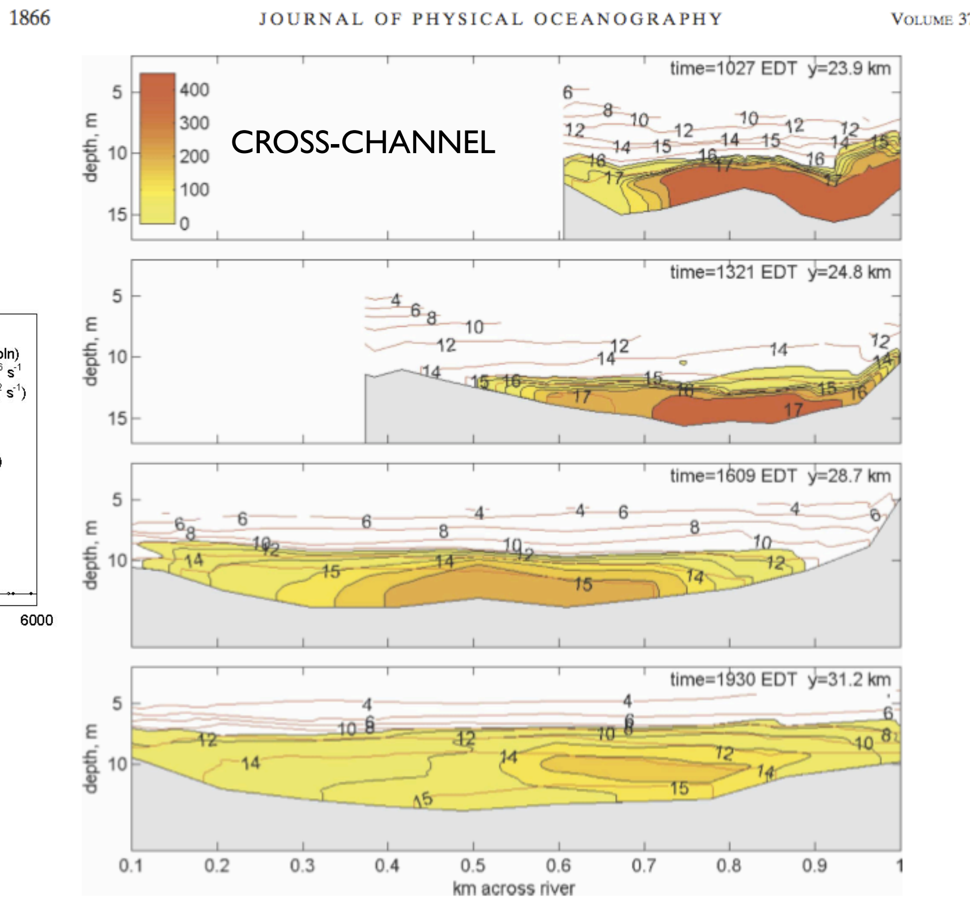


FIG. 6. Cross-channel sections across center of dye patch during the flood tide on 5 May. Color is dye concentration and salinity is red contour.

Implications: Concentration (toxicity) of contaminants, food web structure, etc.

In wider estuaries, wind can drive circulation

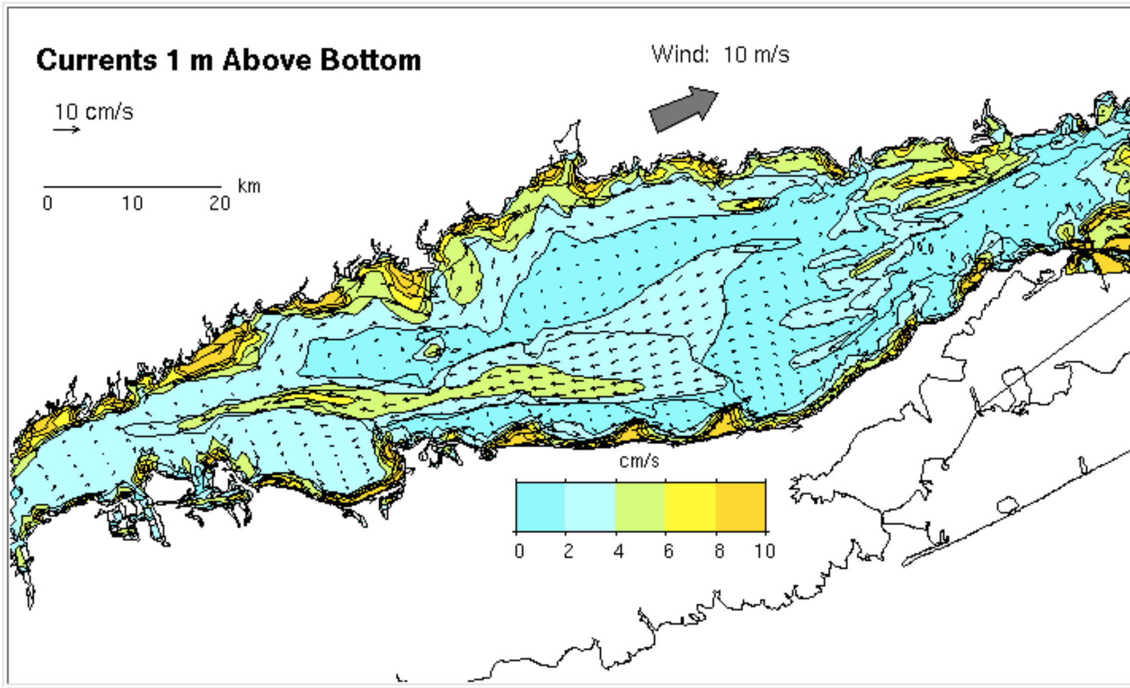


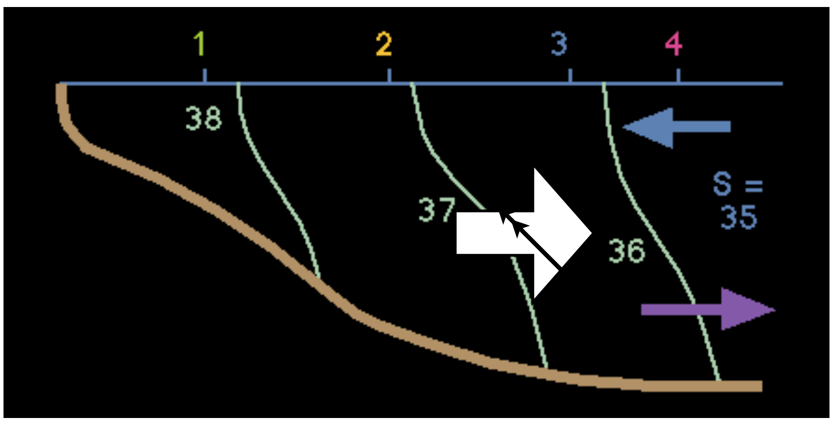
Figure 6. Simulated near-bottom currents (1 m above bottom) during a moderate west-northwesterly wind event (10 m/s).

LIS

http://pubs.usgs.gov/of/1998/of98-502/chapt6/physprop.htm

Inverse Estuaries

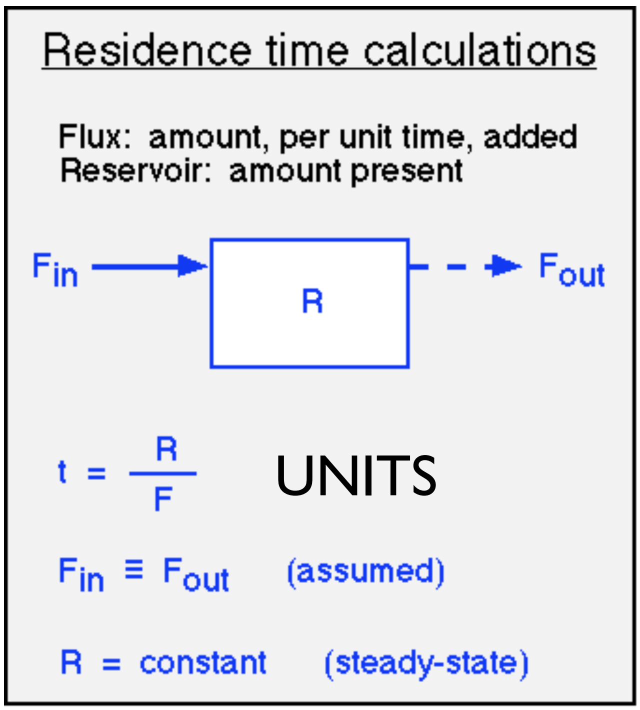
evaporation



lagoonal circulation

Residence time = amount/input = amount/output

Steady State
Averaged property



BOX MODEL APPROACH

But, residence time of what?

If total water, use total F_{in} or F_{out}, but if RW...

Flushing time of river water
(= replacement time of river water in estuary)

Why care?

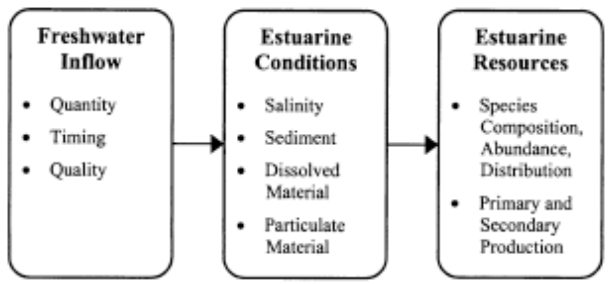


Fig. 1. Schematic diagram of the effects of freshwater inflow on estuaries.

Flushing time (τ_f) is usually calculated according to the fraction of freshwater method outlined by Dyer (1973):

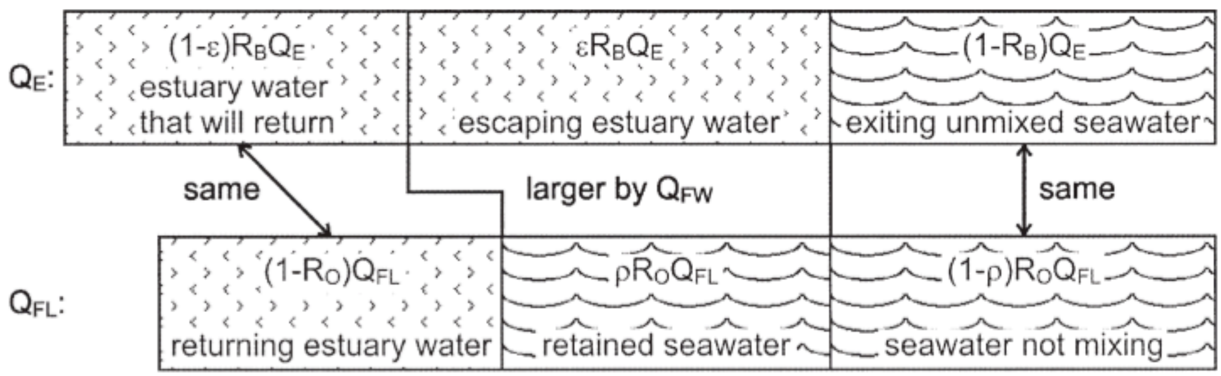
$$\tau_f = \frac{\text{freshwater volume}}{\text{freshwater input}} = \frac{\sum_{i=1}^{n}\left[\left(\frac{S_{sw} - S_i}{S_{sw}}\right)V_i\right]}{Q_f} \qquad (1)$$

where n = number of estuary segments, S_{sw} = seawater end-member salinity, S_i = salinity of segment i, V_i = volume of segment i, and Q_f = freshwater input. To apply this method, the freshwater volume of the estuary is obtained by multiplying the total volume by the fraction of freshwater. The fraction of freshwater is calculated by determining what proportions of freshwater and seawater must have mixed to produce the observed estuarine salinity.

Terminological confusion in literature

What if some of the estuarine water expelled during an ebb returns on the next flood?

We deal with this issue via "exchange" or "return" coefficients:
These terms adjust "exposure time" within estuary for these returns.



$$\tau = \frac{V}{\varepsilon R_B Q_E} = \frac{V}{\rho R_O Q_{FL} + Q_{FW}}$$

Fig. 3. Conceptual representation of ebb (Q_E) and flood (Q_{FL}) tide volumes in an estuary with partial ebb return and incomplete flood mixing. R_BQ_E is that portion of the ebb outflow that is estuary water, and $(1 - R_B)Q_E$ is the portion that is unmixed seawater. R_BQ_E is further divided into a portion ε that escapes the estuary and a portion $(1 - \varepsilon)$ that returns on the next flood tide. R_OQ_{FL} and $(1 - R_O)Q_{FL}$ are as defined in Fig. 2. ρ is that portion of R_OQ_{FL} that mixes into the estuary, and $(1 - \rho)$ is the portion that exits unmixed. Identical water masses in Q_E and Q_{FL} are indicated by arrows; εR_BQ_E is larger than ρR_OQ_{FL} by the freshwater inflow during a tidal cycle, Q_{FW}, which is assumed to mix into the estuary before and during the ebb tide. Turnover time (τ) of the estuary volume V (not shown) can be calculated using either εR_BQ_E or $\rho R_OQ_{FL} + Q_{FW}$.

These principles can be applied to geographical segments as well as water fractions

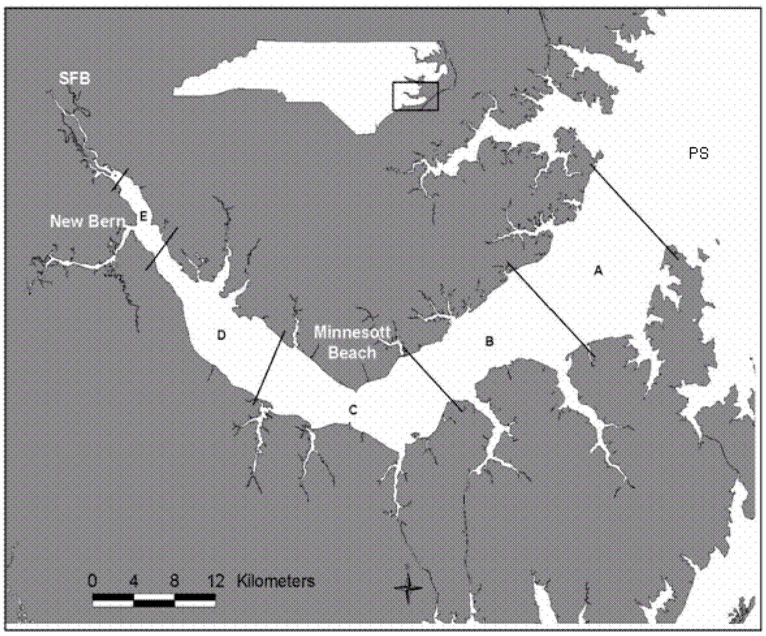


Figure 1. The Neuse River Estuary in central North Carolina. The estuary spans approximately 75 km from Streets Ferry Bridge to the mouth. There is a sharp bend at Minnesott Beach. Estuarine segments A-E were labeled after Christian et al. (1991).

What would be implication for the return coefficient?

Nonsteady state complications
River flow often varies on time scale of flushing time, as do exchange coefficients and other factors affecting salinity (FW fraction)

SUMMARY

What pushes water?

Elevation (river input, tides)
Density changes
Wind
Earth's rotation

What resists the pushing?

Water friction (viscosity)
Wall friction (bottom, sides)